Proton Radiography Capabilities Illuminate Studies of Explosively Driven Fragmentation

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The central mission of the Dynamic Experimentation Division at LANL is the experimental study of the behavior of materials under extreme conditions. Accomplishing this mission requires a comprehensive understanding of the energetic materials (explosives) themselves and of the interaction of detonating explosives with the materials around them. LANL is acknowledged as a world-leading institution in understanding how materials are driven by explosives. Such knowledge is necessary in working with both conventional and nuclear explosives. As a detonation wave passes through an explosive, the pressure immediately behind the wave is on the order of 100,000 atm (100 kbar). A phenomenon known as the Taylor wave immediately begins to reduce this extremely high pressure — but the damage has already been done. This extremely high pressure sends a shock wave into materials adjacent to the explosive, which usually modifies the properties of the material from their initially well-understood values. For instance, the shock wave could harden the material and thereby make it more brittle even before the material has had a chance to move in response to the pressure. This dynamic modification of the materials make explosively driven systems very hard to understand because the properties of the material under dynamic loading are unique to that situation. Thus, it is difficult to reproduce those conditions in the laboratory without actually destroying the laboratory. After the material has been dynamically modified, the Taylor wave will reduce the pressure of the detonation products, but these products are still at a very high pressure. It is this latent pressure that then drives (or pushes) the materials near the explosives.

Understanding the Shear-Banding Process in Explosively Driven Material

The yield strength of some of the strongest steel (i.e., Vascomax 300) is around 15 kbar, which is only about 15% of the pressure immediately behind the detonation wave of an explosive. Therefore, even as the Taylor wave reduces the pressure of the detonation products, the pressure is still near or higher than the strength of the materials in the vicinity. Because these materials are driven by pressures well above their strength, they behave like fluids, including supporting instabilities like many fluid flows. For example, commercially pure titanium (CP Ti) exhibits a shear-banding instability where, as the material is strained at high rates, shear is localized into very thin shear bands. Therefore, as the overall strain in the system increases, the majority of the material is not strained at all; rather, all the strain is concentrated into these regions. Eventually, as these shear-band regions experience significant heating (caused by the strain) and then soften, they will fail and form cracks. This phenomenon can lead an expanding metal driven by explosives to fall apart. Knowledge of such failure mechanisms is important in understanding fragmentation in general (e.g., hand grenades are a case where fragmentation is a desired outcome).

To understand the shear-banding process, we therefore need to explosively drive a shear-banding material (i.e., CP Ti) and watch the temporal evolution of features that appear. However, shear banding is not the only failure mechanism that needs to be understood. Some materials like copper can behave with great ductility even under extreme loading, but they will eventually fail through mechanisms not related to shear banding. Our samples also need to be subjected to a wide variety of stress states, including uniaxial and biaxial stress, because stress will alter the nucleation and development of features. In any failure mechanism, we presume that small perturbations in the material will grow under dynamic loading and eventually form large-scale cracks. Therefore, watching the temporal and spatial evolution of small features allows us to study the failure mechanisms of a material for a given stress state. The pRad capability at LANSCE can accomplish this task with unprecedented temporal and spatial resolution.

The Half-Cylinder Test

The *half cylinder* is a test that we designed to help us understand the fragmentation and failure of an expanding metal cylinder driven by explosives. Fig. 1 describes the arrangement of this test. The outside diameter of the PBX9501 high explosive is 1 in., and its inside diameter is 0.75 in. This explosive system was designed for a series of complementary tests that required the appropriate shock modification of the materials (hence, we use a high-energy explosive, PBX9501). We used a hollow cylinder instead of a full cylinder to eliminate excess energy that could breach the pRad vessel. The explosive is detonated on one end. The detonation wave then travels down the length of the cylinder. The cylindrical geometry provides a stress state in the CP Ti that is principally uniaxial (i.e., hoop stress). This uniaxial stress state would be expected to produce shear bands along the axis of the cylinder. This is fundamentally different from a spherically expanding material, which is subjected to a biaxial stress state. We look at half of a CP Ti cylinder (cut lengthwise) instead of a full cylinder because we want the pRad beam to pass through only one evolving surface. Because pRad is a penetrating diagnostic, if we used a full cylinder, our post-shot analysis would have to disentangle the features from the front and the back sides of the cylinder — a nearly impossible task.

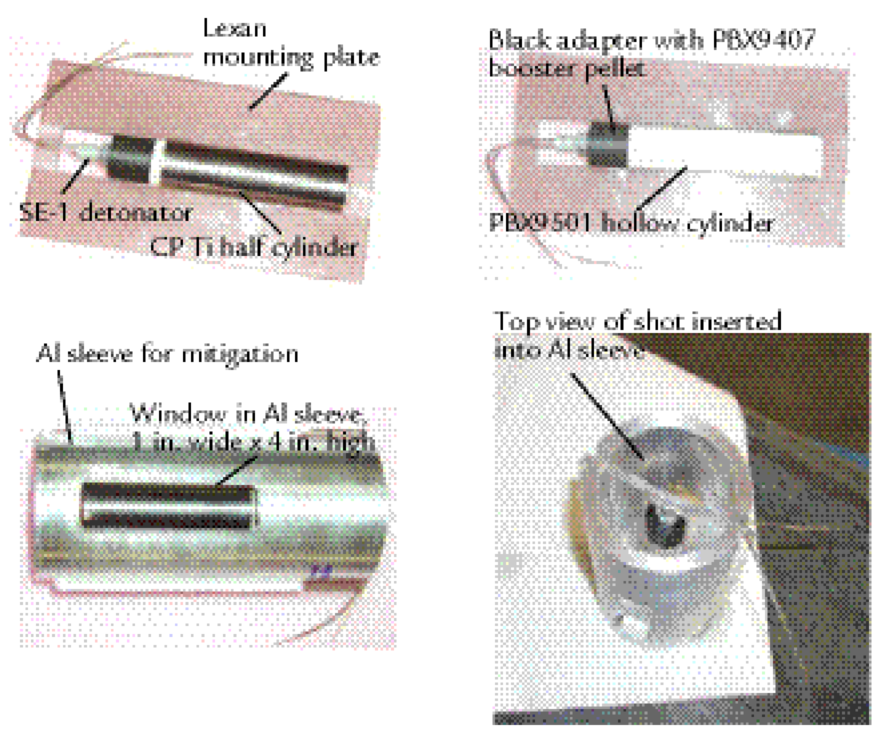

Fig. 1. Arrangement of the half-cylinder test.

Proton Radiography

At the pRad facility at LANSCE, we have fired two such shots with two different CP Ti wall thicknesses: 2 mm for the first shot and 1 mm for the second shot. Although pRad diagnostics produced a detailed time history of these events with approximately 21 images for each shot, we show only 2 images from the first test and 1 image from the second test (Fig. 2). Interestingly, each of the approximately 21 images produced by pRad includes time-history information of the evolution of the cylinder. In the time that it takes for the detonation wave to pass down the length of the cylinder, the portion of the cylinder near the detonator has evolved further (i.e., because of the work done by the gaseous products from the detonation) than has the portion of the cylinder that is at the opposite end of the detonator.

In Fig. 2, the lower portion of the cylinders exhibits no apparent features, but the upper portion of the cylinders exhibits noticeable cracks. We are now focusing our post-shot analysis effort on three avenues. First, we will examine the progressing front between the uncracked and cracked regions to understand the smallest spatial dimension of the features obtained from pRad. Are we actually seeing shear bands, or is the smallest feature that pRad discerns already a crack after the failure of the shear band? Our second approach is to try to understand the nature of the shear-banding instability resulting from geometric changes. For example, more cracks appear in the thinner cylinder (Fig. 2c) than they do in the thicker cylinder (Fig. 2b). This could simply be due to the fact that the instability is related to the interaction of the inner and outer surfaces in the thinner cylinder. Alternatively, because the amount of material being pushed by the explosives has been reduced in the case of the thinner cylinder, the strain rate has been increased. The number of cracks formed may be due to strain-rate effects. We are currently working with modelers in T and X Divisions at LANL to try to more completely understand these influences. Our third approach is to compare these dynamic data produced by pRad with another suite of similarly configured experiments aimed at understanding the same phenomenon. Fig. 3a is a photograph of the two halves of a CP Ti cylinder that was expanded and then stopped at about a 65% overall strain. In the process of stopping the expansion, the outer layer of the CP Ti was melted, and presumably the cracks that are seen have been somewhat modified. To understand how this recovered sample compares to the dynamic situation, we have begun quantitatively comparing the nature of the cracks seen in the dynamic pRad data with an x-ray (Fig. 3a) and a proton radiograph (Fig. 3c) of the recovered sample (Fig. 3b).

The Dynamic Bulge Test

The *dynamic bulge* is a test to study the hemispherical expansion of a copper shell at the pRad facility. This challenging test is the largest one done to date with pRad in terms of the high-explosive load and of the amount of driven materials. A great deal of fragment and blast mitigation was needed to prevent damage to the 6-ft pRad vessel. Good pRad data of the event were difficult to obtain because the test was designed with the detonator in the center of the hemispherical charge — right in the middle of the pRad-diagnostic field of view. Therefore, to see around the detonation system, we arranged the shot at an angle whereby the diagnostics could view the detonation system through only one layer of the shell (like in the half-cylinder test).

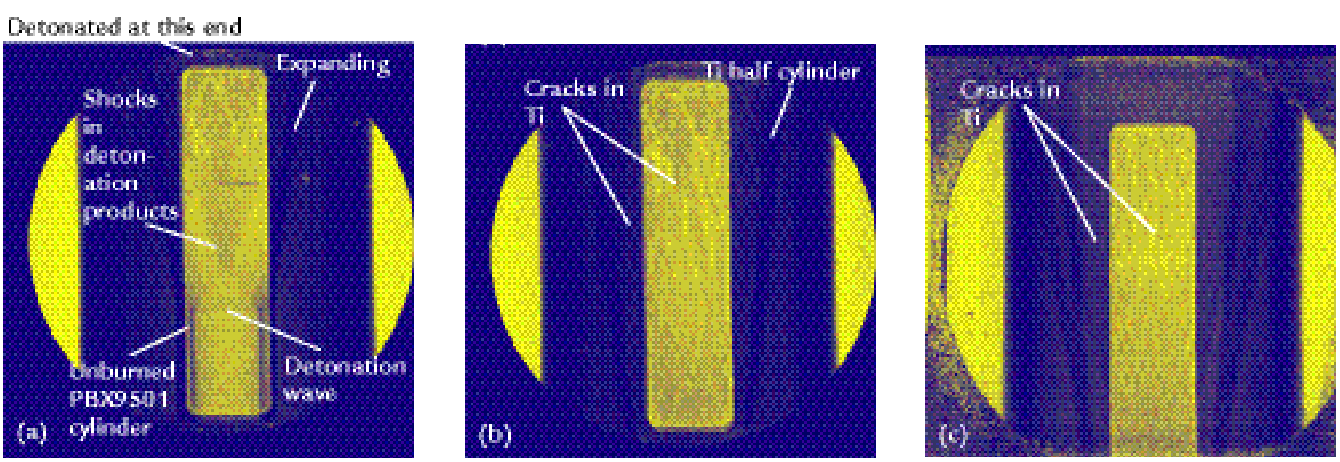

Fig. 2. (a) pRad image of 2-mm half cylinder at 13.6 μs after the detonator was fired. (b) pRad image of 2-mm half cylinder at 20.8 μs after the detonator was fired. (c) pRad image of 1-mm half cylinder at 20.8 μs after the detonator was fired.

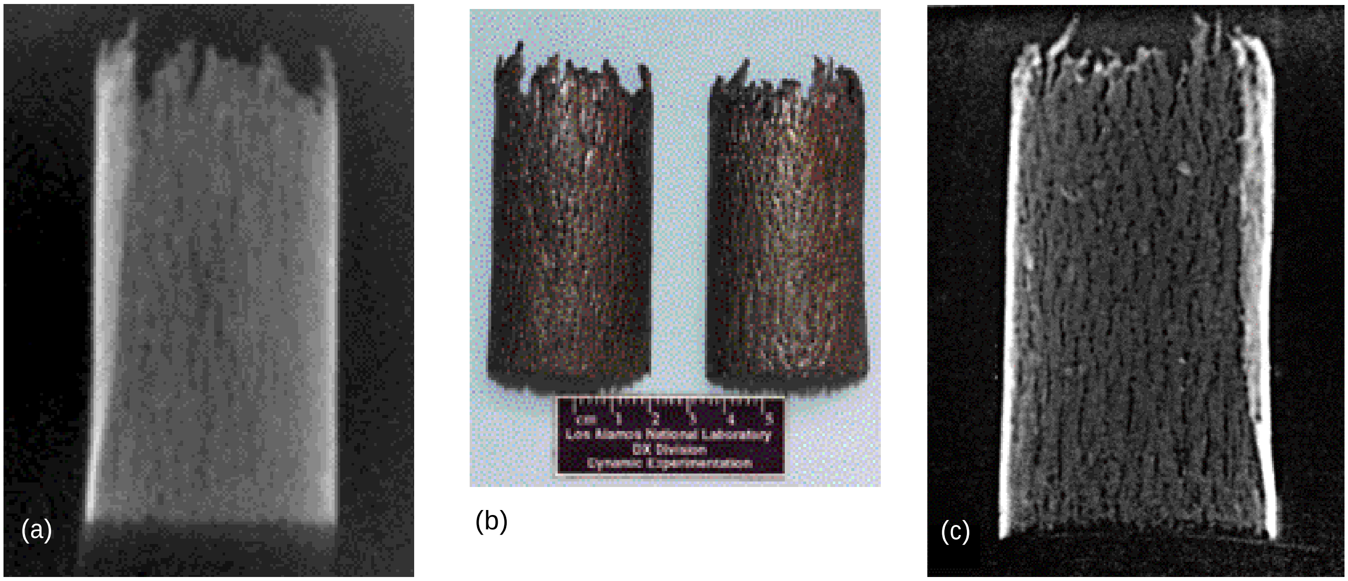

Fig. 3. (a) Static x-ray of a piece of the cylinder on the left-hand side of Fig. 3b. (b) Photographs of two halves of the CP Ti cylinder that was expanded and then stopped at about a 65% overall strain. (c) Static proton radiograph of the half cylinder shown on the right-hand side of Fig 3b.

After overcoming all of these challenges, the data have been initially examined, and we can see the formation of cracks caused by the biaxial stress state induced by the hemispherical geometry. Other tests with this hemispherical geometry are being designed to use smaller charges, to generate more optimized fragment mitigation, and to view experiments using both ductile (copper) and shear-banding (CP Ti) materials. These tests will allow us to study biaxial stress states using a variety of material, sample wall thicknesses, and radii of curvature in a cost-effective manner.

Conclusion

Failure in materials starts with small regions that nucleate damage (i.e., initiation of a shear band). Although the damage in these regions can grow rapidly like a crack or can stay quite small like the thickness of a shear band, it eventually leads to failure of the material. Models developed to treat the huge disparity between the largest and smallest scales involved in failure tend to be extremely complex because they need to simulate unresolved small scales onto the resolved large scales actually being computed. The complexity of these models requires a significant amount of experimental data to both generate and validate the model.

The unprecedented temporal and spatial radiographic ability of the pRad facility to document dynamic events is being used to understand the basic phenomena of failure of expanding materials under the influence of a high-explosive drive. We have developed and fired tests that examine the failure of CP Ti in uniaxial stress and of copper in biaxial stress states. We are beginning to perform detailed analyses of the data obtained from pRad and other tests to understand the influence of material properties, explosive-shock modification, stress state, and geometrical variations involved in the shear-banding instability of CP Ti. Finally, these data will be used to generate and validate modern Advanced Strategic Computing Initiative models of failure.